Development of a Method of Magnetic Structural Analysis of Steel and Cast-Iron Products in Machine-Building

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Abstract. Results of the investigations of the Laboratory of magneto-dynamical methods of testing in development of magnetic structural analysis of steel and cast-iron products in large-scale production are outlined in this report. The techniques have been elaborated for computation of the sensibility of magnetic parameters of a product to magnetic properties of the material, size of the product, its magnetic prehistory, intensity of the magnetizing field. The results were used for development and industrial application of automated devices for magnetic sorting of products.

Introduction.

Required structure and mechanical properties of steel and cast-iron products are achieved by special doping and thermal processing conditions. Possible deviations from these conditions lead to inadmissible changes of structure and demand inspection of the total production output. Such inspection can be performed only by non-destructive methods, the most expanding of which is magnetic testing. Its physical basis are the stable relationships between structure, magnetic and mechanical properties of many ferromagnetic materials.

The gathered experimental data allowed to draw the final conclusions and to present recommendations on the use of magnetic parameters for testing of the quality of annealing, quenching, drawback of steels [1, 2] and cast-irons [1, 3, 4]. The technology of magnetic testing of products made of ferromagnetic steels and cast-irons consists in quick measurement of a given magnetic parameter of the product's material. The determined relationships between parameters of the hysteresis loop of the material and the physico-mechanical properties define the possibilities of magnetic method of testing. The most sensitive parameter to changes in the structure of materials is the coercitive force $\mathbf{H_c}$. While testing large parties of products in motion, the residual magnetization $\mathbf{M_d}$ in a product maintained after magnetizing can be measured non-contactly.

The problem of magnetizing to saturation of structural ferromagnetic materials in a closed magnetic circuit is solved in coercimeters with attached electromagnets [1, 2]. The necessity to test the large-scale production in the industry demands usage of highly productive test tools. One of the ways to solve this problem consists in non-contact magnetizing of products at motion in an open magnetic circuit [5]. Here the achievable intensity of the magnetizing field is not sufficient to magnetize to technical saturation for products with small length to diameter ratio. In [6] it was shown, that at natural cooling of the current coil by the surrounding air in a cylindrical cavity with a radius of 1 cm the stationary field can be achieved with intensity of $\mathbf{H_0}$ = 60 kA/m. The achievable field intensity at a short-termed working regime can be estimated to 100 kA/m, and at an impulse regime -- 200 kA/m. This allows us to perform testing under conditions, when the product is not magnetized to saturation. Let us analyze the possibilities and limitations of the magnetic testing of mechanical properties and structure of products, specified by peculiarities of the magnetizing in an open magnetic circuit.

1. Theoretical analysis of magnetizing of products in an open magnetic circuit.

For the investigation the products of structural materials were conventionally divided according to their magnetic parameters into three groups: “soft”, “medium” and “stiff”. The coercitive force $\mathbf{H_c}$, the saturation magnetization $\mathbf{M_s}$ and the residual magnetization $\mathbf{M_R}$ of the analyzed materials are listed in Table 1.

Table 1. Magnetic properties of the analyzed materials, kA/m.

Magnetic parameters	Materials		
	"Soft"	"Medium"	"Stiff"
$\mathbf{H_C}$	0,2	1	5
$\mathbf{M_S}$	1700	1400	1000
$\mathbf{M_R}$	1400	800	300

Analysis of processes of magnetizing of products in an open magnetic circuit was performed [7-10] based on the analytical expressions, describing magnetizing of a ferromagnetic body and approximating the magnetizing of ferromagnetic materials. As a model of a tested product for visualization a cylinder with the ratio $\boldsymbol{\lambda}$ of length to diameter was used.

1.1. Analysis of changes in sensibility of the method.

In [7] it was shown that at magnetizing in an open magnetic circuit the sensibility of $\mathbf{M_d}$ of a product to structural changes in its material changes as well. This limits the possibilities of application of the method. On Fig. 1 the results of calculations of the sensibility $\mathbf{S^{Md}_{Hcs}}$ of the residual magnetization of a product $\mathbf{M_d}$ to changes of $\mathbf{H_c}$ of its material for different λ of products from the Table 1 are shown.

It was proved that $\mathbf{M_d}$ of products of “stiff” materials can be used for coercimetrical testing only for products with $1.5 \leq \lambda \leq 5$ after magnetizing in a field of $\mathbf{H_e}$ = 200 kA/m. The sensibility $\mathbf{S^{Md}_{Hcs}}$ is in this case > 0.7. For products of all materials with $\boldsymbol{\lambda} \leq 6$ magnetized in the achievable stationary field the sensibility of the parameter $\mathbf{M_d}$ to changes of products sizes increases steeply compared to that of products magnetized to saturation. It makes the requirement to stability of the products sizes stricter at testing by $\mathbf{M_d}$.

1.2. Analysis of influence of the magnetic prehistory of the product.

In [8, 9] the additional limitations of the magnetic testing method were determined at magnetizing of products in an open magnetic circuit, which are caused by the influence of the uncontrollable preliminary magnetization of products on the $\mathbf{M_d}$.

The results introduced on the Fig. 2 show that for long ($\boldsymbol{\lambda}$ = 10) cylinders made of “soft” and “medium” materials magnetized in the field $\mathbf{H_e} \geq$ 25 kA/m the error $\boldsymbol{\sigma}$ is practically zero. For “stiff” materials $\boldsymbol{\sigma}$ stabilizes at around 5% for $\mathbf{H_e} \geq$ 55 kA/m. For

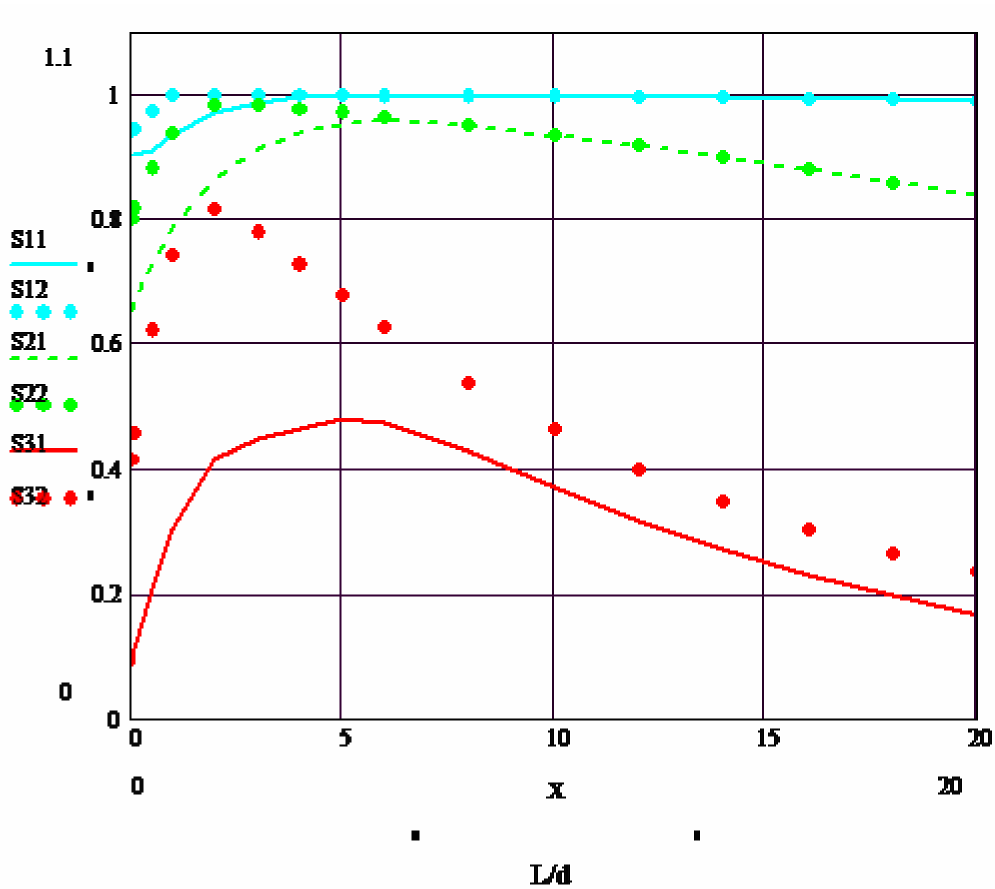
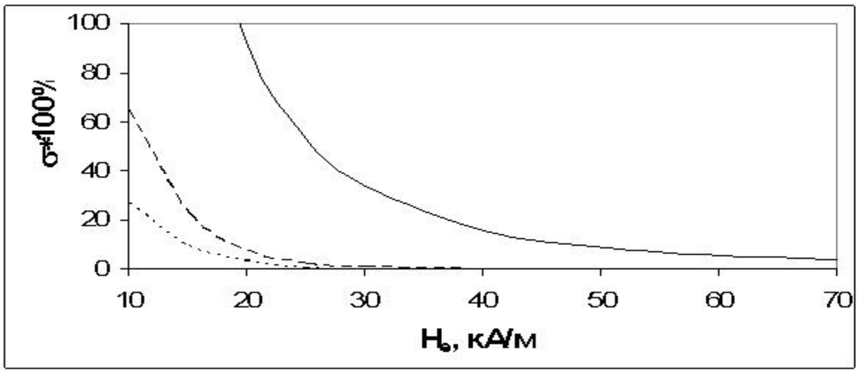


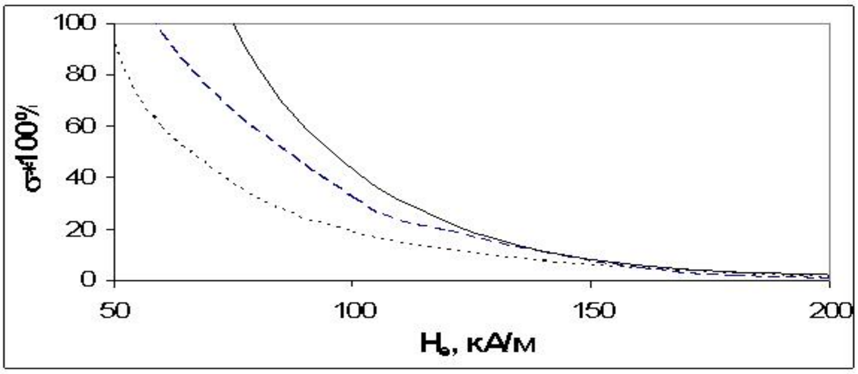
Fig. 1. Influence λ = **L/d** for cylinders made of “soft” (S11, S12), “medium” (S21, S22) and “stiff” (S31, S32) materials according to the Table 1 on the sensibility $\mathbf{S^{Md}_{Hcs}}$ of the informative control parameter $\mathbf{M_d}$ to $\mathbf{H_c}$ of the materials at magnetizing of cylinders in an open magnetic circuit in an external field $\mathbf{H_e}$ = 60 kA/m (S11, S21, S31) and 200 kA/m (S12, S22, S32).

short (λ = 2) cylinders practically of any material $\boldsymbol{\sigma}$ is less than 5% only after magnetizing in fields $\mathbf{H_e} \geq$ 160 kA/m.

The results obtained in [9] show also, that testing with $\boldsymbol{\sigma}$ = 0 for products made of “soft” and “medium” materials is feasible: at magnetizing in fields $\mathbf{H_e}$ =20, 40, 60 and 100 kA/m – at $\lambda \geq$13, 8, 5 and 3.5 correspondingly. At decreasing λ the error sigma increases sharply. When testing by the mentioned fields $\boldsymbol{\sigma}$ = 5% is achieved correspondingly at λ = 11, 6, 4 and 3. For shorter products and weaker fields the testing without warranty of preliminary no-magnetization of products is inadmissible. The testing of products made of a “stiff” material with $\boldsymbol{\sigma} \leq$ 5% is feasible with $\mathbf{H_e}$ = 100 kA/m at $\boldsymbol{\lambda} \geq$4. At $\mathbf{H_e}$ = 60 kA/m for $\boldsymbol{\lambda} \geq$ 7 $\boldsymbol{\sigma}$ =8%.



a).



b).

Fig. 2. Dependence of the maximal error σ for the measurement of $\mathbf{M_d}$ of a cylinder with **λ** = 10 (a) and **λ** = 2 (b) made of “soft” (….), “medium” (----) and “stiff” (____) material, determined by the uncontrollable preliminary magnetization, on the intensity H_e of the magnetizing filed in an open magnetic circuit.

1.3 *Analysis of the offset from the influence of sizes of the tested products.*

The method of testing of products of unstable sizes and simultaneous testing of products of several sizes made of the same material was developed in [10]. The method is based on the results of analysis of the changes in magnetization **M** of the products caused by the decreasing external field $\mathbf{H_e}$ ($-\mathbf{H_c} \leq \mathbf{H_e} \leq \mathbf{H_m}$) after magnetizing by the field $\mathbf{H_m}$ to saturation. It was shown that for products with $\lambda \leq 20$ made of “soft” material the nonlinearity of this dependence does not exceed 0.1%. For products of “medium” materials at $\lambda \leq 20$ and products of “stiff” material at $\lambda \leq 5$ nonlinearly of this dependence does not exceed 1%. For these products the dependence $\mathbf{M}(\mathbf{H_e})$ in the second quadrant of the plane ($\mathbf{M}$, $\mathbf{H_e}$) and the attached to it part of the first quadrant is close to a straight line, crossing the $\mathbf{H_e}$ -axis at the point $\mathbf{H_c}$, the inclination of which to the $\mathbf{H_e}$ - axis is determined by the demagnetizing factor of the product.

As the informative parameter for the sorting of products the relationship $F = \frac{F_d}{(F_d - F1)}$ can be used, where $\mathbf{F_d}$ is the residual magnetic flow in the central cut set of the product, **F1**– the magnetic flow in the product in a field $\mathbf{H_e} = \mathbf{H_I}$.

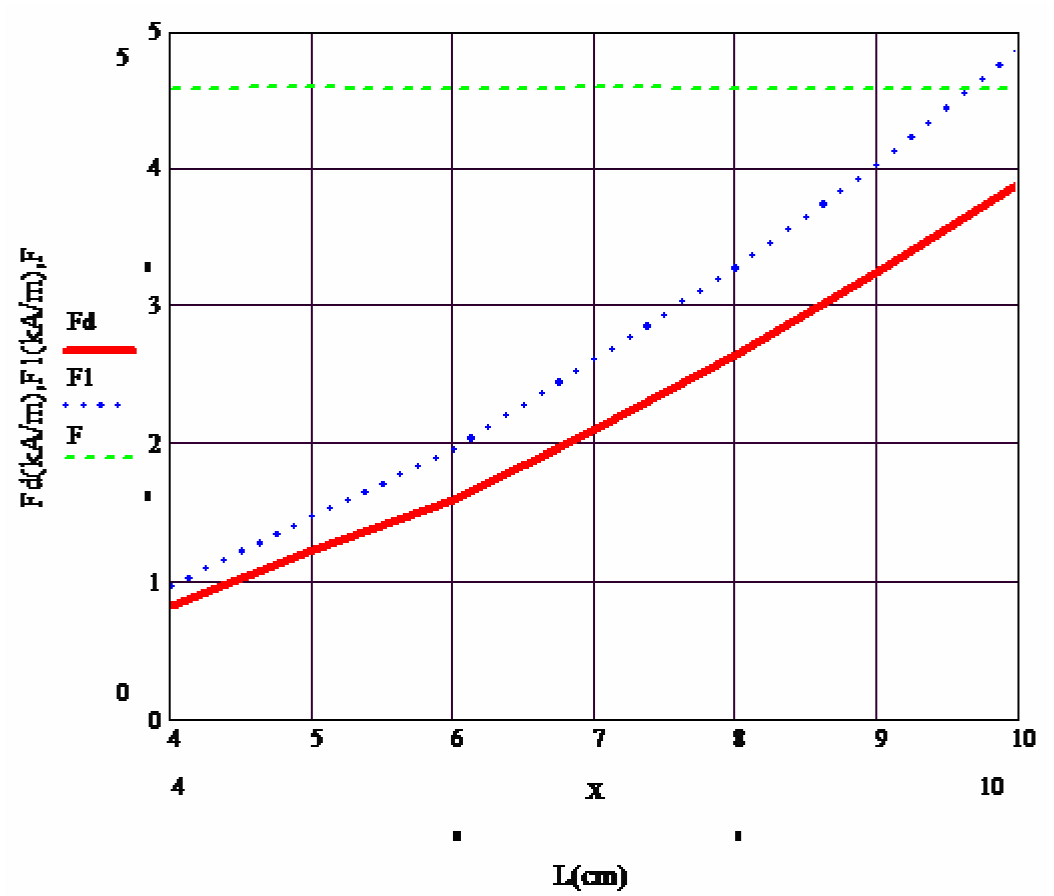


Fig. 3. Results of experimental verification of the elaborated method: **F1**, $\mathbf{F_d}$, **F**.

Fig. 3 presents the results of investigation of the influence of length **L** of products made of steel U7, produced from one stick of a diameter of 6 mm on the magnetic flows **F1**, $\mathbf{F_d}$ and on the relationship **F**. It can be noticed, that at variation of the length of pieces from 40 mm to 100 mm F_d becomes four times larger, while the relationship **F** is practically constant.

The limits for application of the method and the optimal intensity of the field $\mathbf{H_I}$ are determined (the intensity lies within 1-5 kA/m). The developed method at the set regimes of its application is not sensitive to changes in the products parameters. The informative testing parameter is determined only by the $\mathbf{H_c}$ of the products.

2. Instrumental implementation of the method.

2.1 Optimization of the size of the magnetizing coil.

To obtain high productivity of the testing, magnetizing of the products occurs at their movement (along the liner or the transporter) through a coil with stabilized constant current [5]. The inner radius of the coil is determined by the crosscut magnitude of the products. The magnetizing influence of the coil on the product is defined by the intensity H_0 of the field in the center of the coil. For application under industrial conditions it is advisable to use the regime of natural cooling of the coil by the surrounding air. Optimization of the dimensions of the coil with the given internal radius at consideration of the acceptable heating of the coil and the required field intensity $\mathbf{H_0}$ was held in [11].

2.2 *Creating of fields of a given configuration.*

For industrial realization of various techniques of magnetic testing of products in motion the generation of spatially localized homogeneous magnetic field of a given intensity is needed on the way of the products motion.

The physical principles were determined, which allow generation of a lengthy area with homogeneous magnetic field behind the region with the magnetizing field on the products path. The principle consists in use of the effect of equal rates of decrease of a magnetic field on the axis of coils with different inner and outer diameters at different distances from their ends [5, 12]. Effects of generation of homogeneous field and gradient by the Helmholz's coils were also used.

The employment of developed principles allowed to compute the winding data and coils arrangement, which guarantee the magnetizing of products with the field H_0 = 40 - 50 kA/m and of magnetizing field distribution along the products movement axis shown on the Fig. 4.

2.3 The developed technical testing means.

The developed new methods, principles and techniques were realized at creation of a complex of automated highly productive compact devices for magnetic testing of moving small-sized products – devices of the prototype "The Magnetic Quality Analyzer for Steel Products MAKSI" (patent ANB-692), MAKSI-2, MAKSI-P (portable), MAKSI-U (universal) and MAKSI-D (diesel). The appearance of one of the modifications of the MAKSI device is presented on the Fig. 5.

Magnetizing is realized at the free fall of the products through the area with stationary magnetic field with intensity of up to 50 kA/m. Measurement of $\mathbf{M_d}$ is conducted using an inductive converter situated in a region, where the magnetizing field is compensated. Sorting of the products on usable and defective is accomplished according to the result of the $\mathbf{M_d}$ measurement automatically at productivity of 3 products pro second. In the device MAKSI (ANB-692) the possibility is provided to measure also the maximum magnetization of products at magnetizing. In the device MAKSI-2 the possibility to partially demagnetize products before measuring the $\mathbf{M_d}$ exists. In the device MAKSI-P the area with magnetizing field is generated by constant magnets, what makes the converter and the measuring unit of the device compacter. The devices MAKSI-U and MAKSI-D support generation of a magnetic field of the given configuration on the products path and measuring of the magnetic parameter of products at their motion through it. It guarantees an offset from the influence of variations in products sizes on the testing results and increase in sensibility to the surface properties.

The qualitatively new technical characteristics of the developed devices compared with analogues are confirmed by the results of metrological certification, their successful integration in industry of Belarus and Russia. On the Minsk Factory of the Heating Equipment an automated testing line was constructed to control the structure of non-grinded casts of nipples made of malleable cast-iron with productivity of up to 70 000 items pro 24 hours, and an automated section for testing of structure of cast-iron fittings of more than 20 types before mechanical treatment.

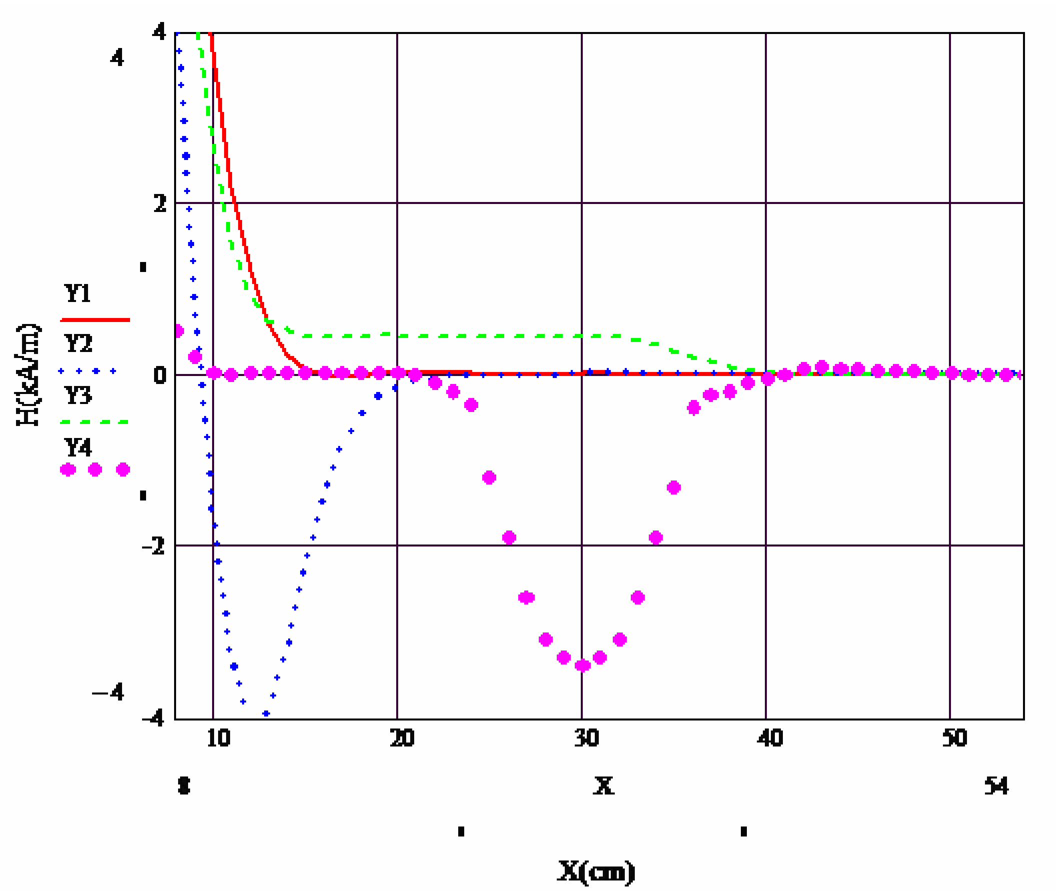


Fig. 4. Possible distributions of the magnetic field along the axis of the products motion in the control region.

Fig. 5. Appearance of a recent modification of the device MAKSI.

On the branch of the Minsk Motor Plant in Stolbtsy a section was constructed for testing of the thermal treatment quality and mechanical properties for tenths of designations of critical components of engines.

3. The recommended application areas.

Investigation of the properties of steels after various thermal treatments [1] have allowed to determine the main application areas of the method of magnetic testing of structure and mechanical properties of products by $\mathbf{M_d}$. This includes testing of the structural state and strength characteristics of the thermally treated products (annealing, normalization, quenching, tempering, aging treatment), sorting of products according to the steel grade, qualitative estimation of the amount of the alloying elements.

The carried out analysis [3, 4] has revealed, that sorting of the cast-iron casts with different structure from one another based on the measurement of $\mathbf{M_d}$ can be recommended for:

-- separation of white cast-iron from cast-irons of other grades (including for quality control by annealing of the white cast-iron to malleable);

-- sorting of pearlite and ferrite cast-iron of all grades from one another (the possibility exists of quantitative analysis of the ferrite - pearlite ratio in malleable and high-strength cast-iron);

-- testing of form of graphite enclosures in cast-iron at constant structure of the metallic matrix. When the change of metallic matrix is possible and at occurance of lamellar graphite in high-strength cast-iron a confident separation of ferrite high-strength cast-iron from the gray one is feasible.

4. Conclusions.

As a result of the carried out research a scientific foundation was created for development of magnetic testing tools for controlling the physico-mechanical properties and structure of products of the machine-building industry. Analytical patterns of relationship are obtained, as well as calculation techniques for sensibility of magnetic parameters of a body to variations in the basic magnetic characteristics of the material, dimensions of the body, its magnetic prehistory, intensity of magnetizing field. Physical limitations were determined for the magnetic testing at magnetizing of products in an open magnetic circuit. Recommendations were elaborated for the method application considering achievable in practice stationary and impulse magnetic fields. Novel results in the domain of analysis of magnetization formation of products allow to choose soundly the magnetic parameter necessary for solving of the magnetic testing problem, the mean of measurement, magnetizing field intensity, arrangement and characteristics of measuring converters.

The theory and general principles were found for development of means of non-destructive testing of mechanical properties of products made of ferromagnetic materials of mass production. The principles of building of systems for magnetizing of moving small-sized products were developed, which guarantee to minimize the system weight, and allow to measure the magnetic flow in the product in a given field in the direct adjacency to the area of stationary magnetizing and demagnetizing field, to decrease the sizes of testing devices and measurement times. The principles were developed for construction and processing of signals of induction converters, which guarantee testing of properties of moving products in a wide range of movement rates of the products and amplitudes of the converters signals.

The derived principles were used at creation of automated highly productive devices of magnetic sorting of moving products -- “Magnetic Analyzer of the Quality of Products Structure MAKSI”.

Reference.

[1] Miheev M.H., Gorkunov E.S. Magnetic methods of structural analysis and non- destructive testing. M.: Nauka, 1993. p. 252

[2] Gorkunov E.S. Magnetic devices for testing of structure and mechanical properties of steel and cast-iron products (Review). - Defectoscopiya, 1992, Nr. 10, pp. 3-35.

[3] Gorkunov E.S., Somova V.M., Nichipuruk A.P. Magnetic properties and methods of testing of structure and strength characteristics of cast-iron products (Review). - Defectoscopiya, 1994, Nr. 10, pp. 54-82.

[4] Sandomirski S.G. Possibilities and limitations of the magnetic testing of structure of cast-iron molds (Review). -- Foundry and metallurgy, 2002, Nr. 3, pp. 41-44.

[5] Sandomirski S.G. Magnetic testing of physico-mechanical properties of products of mass-production at motion (Review). - Defectoscopiya, 1996, Nr. 7, pp. 25-45.

[6] Sandomirski S.G. Optimization of geometrical dimensions of magnetizing coil of the tools for magnetic testing of moving ferromagnetic products. - Defectoscopiya, 1989, Nr. 7, pp. 72-79.

[7] Sandomirski S.G. Measurement of sensibility of magnetic method of testing of physico-mechanical properties of steels at magnetizing of products in an open magnetic circuit (limitations of the method possibilities). - Defectoscopiya, 1998,Nr. 7, pp. 72-81.

[8] Sandomirski S.G., Sandomirskaya E.G. Influence of magnetic prehistory of a product on the results of testing of its physico-mechanical properties by a magnetic method at magnetizing in an open magnetic circuit (limitations of the methods possibilities). 1. Model experiment. - Defectoscopiya, 2004, Nr. 6, pp. 63-71.

[9] Sandomirski S.G. Influence of the magnetic prehistory of a product on the result of testing of its physico-mechanical properties by a magnetic method at magnetizing in an open magnetic circuit (limitations of the methods possibilities). 2. Analytical modeling.- Defectoscopiya, 2004, Nr. 6, pp. 72-79.

[10] Sandomirski S.G. Analysis of the method of testing of moving ferromagnetic products by the coercitive force. - Defectoscopiya, 1991, Nr. 6, pp. 27-34.

[11] Sandomirski S.G. Optimization of geometric dimensions of magnetizing coil of the tools for magnetic testing of moving ferromagnetic products. - Defectoscopiya, 1989, Nr. 7, pp. 72-80.

[12] Sandomirski S.G., Melguy M.A., Sandomirskaya E.G. Optimization of the magnetizing field configuration in instruments of magnetic testing of the moving ferromagnetic products. – Defectoscopiya, 1990, Nr. 3, pp. 19-24.